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IMPLICATIONS OF ATMOSPHERIC TEMPERATURE FLUCTUATIONS ON PASSIVE REMOTE SENSING OF CHEMICALS

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ABSTRACT

Passive remote sensing of airborne chemicals at infrared wavelengths may be limited by temporal fluctuations in atmospheric brightness temperatures $\delta T(\Delta t)$. The fluctuations δT increase the minimum detectable chemical vapor concentration-pathlength product (CL) given by the noise-equivalent-CL (NECL) of the measurements scenario. Brightness temperatures in two infrared spectral bands were measured on clear and cloudy days along three lines of sights. For time windows Δt < 3-5 *s*, $\delta T(\Delta t)$ remained constant at the sensor noise-level and rapidly increased as Δt increased. The fluctuation time scale for the cloudy day was longer than those for the clear day and the magnitude of the fluctuations was smaller. At the conditions of clear day tests, passive remote sensing of airborne chemicals would have reached its maximum sensitivity with an integration interval Δt = *3-5 s* with sensitivity diminishing fast with longer detection time-windows.

1. INTRODUCTION

Passive remote sensors of airborne chemicals and particulates using long wave IR (LWIR, also known as the "thermal infrared" region) spectroscopy are being used extensively for environmental enforcement, atmospheric science, and domestic security applications. In such applications, LWIR radiation from naturally occurring targets in the background (e.g., buildings or the sky) is detected and absorption (or emission) features of chemicals, such as contaminants, interferants, or atmospheric species, are measured and analyzed spectrally. For passive detection of chemicals, measurement sensitivity increases as the brightness temperature difference, ΔT, between the target chemical and the radiative background source increases. When the atmosphere and the radiating background are near thermodynamic equilibrium, the brightness temperature difference is small (e.g., $\Delta T < 1$ *K*), and slight variations in ΔT, which may be induced by atmospheric fluctuations, such as wind and turbulence, can significantly affect the measurement. Such variations limit the measurement accuracy, even when other parameters (e.g., detector noise) are well controlled throughout the measurement period. Furthermore, when measurements require long data collection cycles (e.g., 10 – 20 *s*), atmospheric fluctuations, which characteristically occur at a long time scale, may introduce noise that significantly exceeds other noise components, thereby becoming the sensitivity limiting parameter.

Let assume a typical scenario where a passive IR sensor is viewing a chemical vapor at temperature T and concentration C (g/m^3) over pathlength L (m) that is illuminated from behind (background radiation) by a blackbody radiation B(T+ΔT) (e.g., radiation emitted by a topographical object. modeled by the Planck function B). For this measurements scenario the minimum detectable concentration-pathlength product (CL) for the chemical vapor is given by

$$NECL = \frac{NESR}{\alpha\,[B(T+\Delta T) - B(T)]} \cong \frac{NESR}{\alpha\; B(T)\; 0.0162\; \Delta T} \qquad (1)$$

In Eq. (1) NECL is the noise-equivalent-CL (g/m^2), NESR is noise-equivalent-spectral-radiance of the sensor (W/cm^2/sr/cm^{-1}), α is the chemical vapor absorption coefficient (m^2/g) and ΔT (K) is the temperature difference the chemical vapor and the incidence background radiance. The approximation $B(T+\Delta T) - B(T) = B(T)\; 0.0162\; \Delta T$ is accurate within 5% for wavenumber 1000 cm^{-1}, T = 300 K and |ΔT| < 10 K. Eq. (1) shows that the minimum detectable chemical vapor is inversely proportional to ΔT when it is implicitly assumed that the temperature T and the thermal contrast ΔT are held constant.

When a chemical vapor is placed in the atmosphere, its temperature fluctuates with the ambient temperature. Thus, the thermal contrast ΔT between the background radiance and the vapor will fluctuate as well and affect the minimum detectable NECL given in Eq. (1). As a

result of δT fluctuations in ΔT the NECL will increase by $\delta NECL$ given by

$$\delta NECL = \frac{\partial NECL}{\partial \Delta T}\delta T = NECL\frac{\delta T}{\Delta T} \qquad (2)$$

Thus, the increase of the minimum detectable concentration- pathlength product is directly proportional to the atmospheric temperature fluctuations δT.

In this paper we will show measurements of δT fluctuations from which the reader may infer the effect on NECL. Complete and detailed information pertain to this paper can be obtained from our recent publication Ben-David et al. (2005).

2. RESULTS AND DISCUSSION

The effect of atmospheric brightness temperature fluctuations $\delta T(\Delta t)$ on passive remote sensing measurements was measured and analyzed by simultaneously measuring the time dependent $T(t)$ by two low-noise ($\delta T \sim 30$ *mK*) MCT detectors equipped with band-pass filters (centered at 9.82 μm and 10.52 μm) at a temporal resolution of *0.01 s* (100 Hz).

Measurements were repeated on a clear day and a cloudy day and along three nearly horizontal lines of sights (LOS). The sensor was pointed with LOS toward a building at 0.5 *km*, a mountain at 6 *km* and the horizon. The brightness temperature measurements are given in Figs. 1-2.

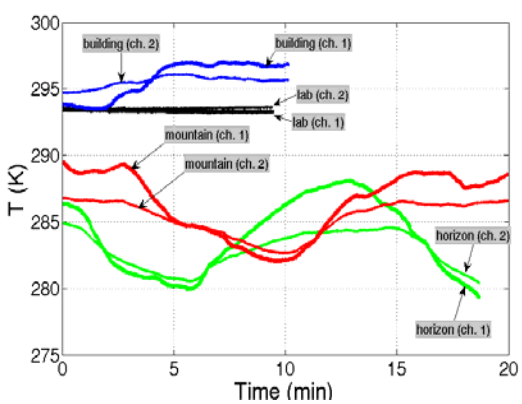

Fig. 1. Variation of the brightness temperature with time as measured in a clear day (afternoon) by detector 1 (thick lines) and detector 2 (thin lines) for line of sight pointing toward (1) a building at 0.5 km (blue), (2) a mountain at 6 km (red), (3) the horizon (green), and (4) a blackbody at room temperature in the lab (black). Note: the two detectors measurements are simultaneous for each line of sight but the measurements for the three lines of sight are not simultaneous and were taken within ~ 1 hour.

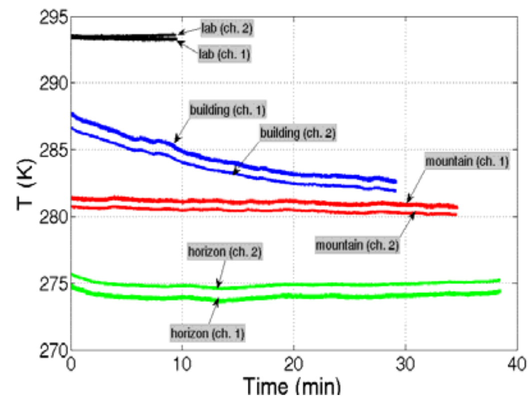

Fig. 2. Same as Fig. 1 but for a cloudy day (morning). The measurements for the three lines of sight are not simultaneous and were taken within ~ 2 hours.

The non-stationary measurements (wide-sense stationary) were analyzed for atmospheric brightness temperature fluctuations $\delta T(\Delta t)$ by segmenting the data into various time intervals Δt and computing the standard deviation within each segment. Results of all measurements (i.e., both days and along all three line of sights) showed that the detector noise limit of $\delta T \sim 30$ *mK* (i.e., 3 $mk/\sqrt{Hz}$) was achieved in all measurements in which $\Delta t < \sim 3$ *s*.

On the clear day (Fig. 3), as the time interval increased beyond 3-5 *s*, the brightness temperature fluctuations increased rapidly to a few tenths of a degree. As Δt increases beyond 3-5 s, $\delta T(\Delta t)$ increases dramatically until at Δt = *100* s, $\delta T(\Delta t) \rightarrow$ *hundreds mK*. At $\Delta t > 20$ s, $\delta T(\Delta t) >$ *100 mK* for the mountain and horizon LOS. This is significantly higher than the measured detector limit of *~30 mK* and thus suggests that the advantage offered by cooled MCT detectors is no longer realized. Clearly, such large fluctuations exceed significantly any detector or sensor noise and can seriously limit any radiometric passive remote sensing application.

Fig. 4 shows the brightness temperature fluctuations $\delta T(\Delta t)$ of the channel 1 data obtained on the cloudy day, corresponding to Fig. 2 (similar results, not shown here, were obtained for channel 2). As in Fig. 3, the detector (or sensor) noise limit of 3 $mk/\sqrt{Hz}$ was reached in the lab and in all outdoors tests with detection window of $\Delta t < 10$ *s*. As Δt increased beyond 10 *s*, $\delta T(\Delta t)$ increased to 0.1 K. Consistent with the results of Fig. 2, the brightness temperature fluctuations are smaller than those for the clear day (Fig. 3). Here, the benefit of longer integration time (and thus larger total signal) can be slightly extended, relative to the conditions that prevailed in the clear day, without increasing the noise level. However, as Δ*t* increases beyond 10 *s*, the noise

increases rapidly and eliminates the advantage of longer integration times, even at relatively uniform atmospheric conditions.

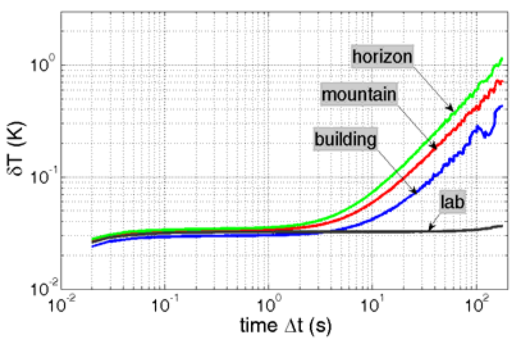

Fig. 3. Variation of brightness temperature fluctuations δT with detection time window Δt as seen by channel 1 for a clear day using brightness temperature measurements shown in Fig. 1.

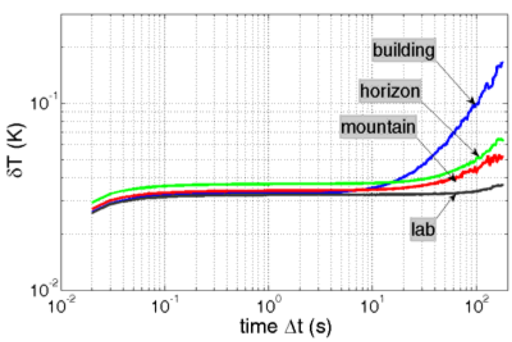

Fig. 4. Variation of brightness temperature fluctuations δT with detection time window Δt as seen by detector 1 for a cloudy day using brightness temperature measurements shown in Fig. 2.

A possible explanation for the difference between the clear day and the cloudy day measurements of $\delta T(\Delta t)$ is that the atmosphere of the cloudy day was more thermally uniform. The cloud layer is a radiating blackbody source (the emissivity of a thick cloud is nearly unity) and the deep cold sky, which is the main factor for the elevation angle dependence of infrared brightness temperature in the atmosphere, is shielded by the presence of clouds. Thus, a cloudy sky tends to originate thermodynamic equilibrium (for the line of sight) and reduces differences among brightness temperatures observed at different wavelengths, enhancing their temporal correlation. By analyzing the autocorrelation function of these measurements it was demonstrated (Ben-David et. al 2005) that the data is highly correlated up to ~30 *s* in the clear day tests and ~100 *s* in the cloudy day tests. This strong correlation, even at frequencies as slow as 0.01 *Hz*, suggests that atmospheric turbulence eddies may be the source for these brightness temperature fluctuations.

The spectral band of one of the detectors overlaps the absorption features of O_3 and water vapor, whereas the other band overlaps the absorption by CO_2 and water vapor, temperature variations among eddies must affect the spectral features detected by one channel differently from the other. Thus, as eddies are transported within the field of view, temperature variations among these eddies result in variations in the brightness temperature between the two channels. This was demonstrated by analyzing the spectral coherence of the two channels (Ben-David et al. 2005).

3. SUMMARY

Measurements of atmospheric brightness temperature fluctuations suggest that the sensitivity and specificity of various passive remote sensing techniques may be seriously limited by atmospheric fluctuations. When the detection time window Δt exceeds 3- 5 *s*, depending on the atmospheric conditions at the time of measurement, random fluctuations as high as a few tenths of degrees may introduce measurement uncertainty that exceeds the detector (sensor) noise. The fluctuation time scale for the cloudy day was longer than that for the clear day, and the magnitude of the fluctuations was smaller.

This fact that $\delta T(\Delta t > 3\text{-}5\ s)$ is significantly higher than the measured detector noise limit of *~30 mK* suggests that the advantage offered by cooled MCT detectors is no longer realized. Furthermore, extending Δt just increases the fluctuations $\delta T(\Delta t)$ and further reduces the measurement sensitivity. At the conditions of clear day tests, passive remote sensing (e.g, Fourier Transform IR sensors) of airborne chemicals would have reached its maximum sensitivity with an integration interval $\Delta t = 3\text{-}5\ s$ and with sensitivity diminishing fast with longer detection time-windows. This counter-intuitive observation may impact remote sensing applications.

The fluctuations δT will increase the minimum detectable chemical vapor concentration-pathlength product (CL) given by the noise-equivalent-CL (NECL) of the measurements scenario.

RFERENCES

Ben-David A., S. K. Holland, G Laufer, and J. D. Baker, 2005: Measurements of Atmospheric Brightness Temperature Fluctuations and Their Implications on Passive remote Sensing in Optics Express **13**, 8781-8800.